AD-A271 182

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE 06/17/93	3. REPORT TYPE AND DATES COVERED Final/25June'90 - 24June'93

4. TITLE AND SUBTITLE
The Ductile to Brittle Transition in Polycrystalline Ice Under Compression

5. FUNDING NUMBERS
DAAL03-90-G-0141

6. AUTHOR(S)
Erland M. Schulson

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Dartmouth College
Thayer School of Engineering
8000 Cummings Hall
Hanover, NH 03755-8000

DTIC ELECTE OCT 21 1993 S B D

8. PERFORMING ORGANIZATION REPORT NUMBER
536577

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army Research Office
P. O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ARO 27482.7-GS

11. SUPPLEMENTARY NOTES
The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Under monotonically increasing compressive loading, polycrystalline ice undergoes a transition from ductile to brittle behavior upon increasing the strain rate to above a critical level. Correspondingly, the dependence of the failure stress on the strain rate changes from strongly positive to weakly negative; i.e., from strain rate hardening to moderate strain rate softening. Also, upon reaching the transition, the failure stress becomes dependent upon grain size, increasing as the grain size decreases. These characteristics indicate that different deformation mechanisms operate on either side of the transition. They indicate further that the transition marks the point at which the ice reaches its highest strength. In practical terms the ductile-to-brittle transition sets the maximum force a moving ice cover (e.g., on a river) exerts against an obstacle (e.g., a bridge pier).

The problem, therefore, is to understand the origin of this transition.

To this end a systematic experimental investigation was carried out at -10°C on columnar, fresh-water ice. The work was guided by the hypothesis that the transition occurs when cracks, nucleated during loading, begin to propagate. The hypothesis was verified.

14. SUBJECT TERMS	15. NUMBER OF PAGES 3
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std Z39-18
298-102

THE DUCTILE TO BRITTLE TRANSITION IN POLYCRYSTALLINE ICE UNDER COMPRESSION

FINAL REPORT

ERLAND M. SCHULSON

AUGUST 17, 1993

U.S. ARMY RESEARCH OFFICE

DAAL03-90-G-0141

THAYER SCHOOL OF ENGINEERING

DARTMOUTH COLLEGE

HANOVER, NEW HAMPSHIRE 03755

Final Report

1. Problem Statement

Under monotonically increasing compressive loading, polycrystalline ice undergoes a transition from ductile to brittle behavior upon increasing the strain rate to above a critical level. Correspondingly, the dependence of the failure stress on the strain rate changes from strongly positive to weakly negative; i.e., from strain rate hardening to moderate strain rate softening. Also, upon reaching the transition, the failure stress becomes dependent upon grain size, increasing as the grain size decreases. These characteristics indicate that different deformation mechanisms operate on either side of the transition. They indicate further that the transition marks the point at which the ice reaches its highest strength. In practical terms the ductile-to-brittle transition sets the maximum force a moving ice cover (e.g., on a river) exerts against an obstacle (e.g., a bridge pier).

The problem, therefore, is to understand the origin of this transition.

To this end a systematic experimental investigation was carried out at -10°C on columnar, fresh-water ice. The work was guided by the hypothesis that the transition occurs when cracks, nucleated during loading, begin to propagate.

2. Most Significant Results:

1. Under uniaxial compressive loading across the columns, grain boundaries crack when inclined to the loading direction. From these "parent" cracks extensions form along the loading direction. These extensions are termed wing cracks. Wing cracks form on both sides of the transition. Under increasing stress at strain rates above the transition rate, the wings lengthen in a stable manner and eventually split the material into a number of rather crack-free pieces. The wing cracks do not propagate under increasing stress at strain rates on the ductile side of the transition. The hypothesis is thus verified.

2. Crack-tip creep suppresses wing crack growth. For instance, crack growth can be stopped by holding a wing crack under constant stress for a sufficiently long time.

3. The transition strain rate increases with decreasing grain size and is consistent with functionality of the form (grain size)$^{-3/2}$.

4. These results can be explained in terms of the competition between the build-up and the relaxation of stresses at the tips of the wing cracks. At high strain rates the build-up dominates and the cracks propagate. At low strain rates the relaxation dominates and the cracks are "blunted". The transition strain rate, $\dot{\varepsilon}_{D/B}$, can thus be modeled by incorporating the crack size (which is set by the grain size, *d*) and the resistance to creep, to fracture and to frictional sliding across the surface of the inclined, parent crack. Accordingly,

$$\dot{\varepsilon}_{D/B} = \frac{4ZBK_{IC}^{3}}{3\pi f(1-\mu)d^{3/2}}$$

where Z is a dimensionless constant, B is the co-efficient from the power law describing secondary creep ($\dot{\varepsilon} = B\sigma^3$) K_{IC} is the critical stress intensity factor for mode-I crack growth, μ is the co-efficient of sliding friction for ice on ice and *f* is size of the creep zone relative to the parent crack.

A detailed description of the above work may be obtained from the papers listed below.

5. The experiments have also revealed that the transition strain rate depends upon confinement. Under biaxial loading across the columnar grains, $\dot{\varepsilon}_{D/B}$ first increases and then decreases with increasing confinement. This effect is reported in Progress Reports 5 and 6. It will be explored further at a later date. Meanwhile, the effect is being analyzed.

3. *Publications*

3.1 with support from this grant only:

"A Preliminary Investigation of the Ductile-Brittle Transition in Columnar S2 Ice Under Compression"
R.A. Batto and E.M. Schulson
Proc. IAHR Ice Symp. (1992) 1021-1034.

"On the Ductile-To-Brittle Transition in Ice Under Compression"
R.A. Batto and E.M. Schulson
Acta metall. mater. 41 (1993) 2219-2225.

"Ductile-to-Brittle Transition in Ice Under Compression: Grain Size Effect"
R.A. Batto and E.M. Schulson
ASME - AMD 163 (1993) 229-234

"An Investigation of the Ductile-Brittle Transition in Columnar S2 Ice Under Compression"
R.A. Batto
Master of Engineering Thesis, June 1992.

3.2 with minor support from this grant and major support from another:

"The Brittle Compressive Failure of Fresh-Water Columnar Ice Under Biaxial Loading"
T.R. Smith and E.M. Schulson
Acta metall. mater. 41 (1993) 153-163.

"Ductile Ice"
E.M. Schulson and G. A. Kuehn
Phil. Mag. 67 (1993) 151-157.

4. *Scientific Personnel Supported:*

Rachel Batto, M.E. (June 1992)
Stephanie Buck
Erland Schulson

The views, opinions, and/or findings contained in this report are those of the author (s) and should not be construed as an official Department of the Army position, policy or decision unless so designated by other documentation.